Progress report on friction loss of slurries in straight tubes

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Progress report on friction loss of slurries in straight tubes

Abstract
This progress report summarizes the work to date on the experimental evaluation of the head loss of slurries flowing in horizontal and vertical tubes. The slurries used in the investigation were spherical glass beads and ion exchange resin particles suspended in water. The tube size used was approximately 0.3-in. inside diameter. Concentrations from zero to approximately 50 percent by weight were used.
PROGRESS REPORT ON FRICTION LOSS
OF SLURRIES IN STRAIGHT TUBES

by

Glenn Murphy, Michael A. McCoy, and
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AMES LABORATORY
RESEARCH AND DEVELOPMENT REPORT
U.S.A.E.C.
PROGRESS REPORT ON FRICTION LOSS
OF SLURRIES IN STRAIGHT TUBES

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Glenn Murphy, Michael A. McCoy, and
Harold E. Wolfe

September 1960

Ames Laboratory
at
Iowa State University of Science and Technology
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PROGRESS REPORT ON FRICTION LOSS OF SLURRIES IN STRAIGHT TUBES

Glenn Murphy, Michael A. McCoy, and Harold E. Wolfe

ABSTRACT

This progress report summarizes the work to date on the experimental evaluation of the head loss of slurries flowing in horizontal and vertical tubes. The slurries used in the investigation were spherical glass beads and ion exchange resin particles suspended in water. The tube size used was approximately 0.3-in. inside diameter. Concentrations from zero to approximately 50 percent by weight were used.

The results are presented in graphical form as head loss in feet of mixture vs. Froude number and a "Z-factor" vs. Froude number. The Z-factor is evaluated as the ratio of the pressure drop of the pure fluid to the pressure drop of the mixture flowing at the same mean velocity. The relationship between the Z-factor for turbulent flow and concentration is presented in graphical form for the three directions of flow.
I. INTRODUCTION

The object of this report is to present the experimental data obtained from a study of the head loss in a solid-liquid mixture flowing in horizontal and vertical tubes. The tests were conducted in 0.3-in. inside diameter glass tubes with glass beads of 0.0028-in. average diameter, with glass beads of 0.0013-in. average diameter, and with ion-exchange resin beads of 0.0044-in. average diameter suspended in water. Weight concentrations (pounds of solid per pound of mixture) were varied from approximately 4 to 50 per cent by weight and the average temperature was 20°C.

This report follows an earlier report\(^1\) on the investigation of the flow properties of slurries in horizontal tubes. A correlation of data for flow in vertical tubes is now in progress but is not included in this report. The data taken are summarized in the appendix, and plots of head loss vs. Froude number and plots of Z-factor (ratio of pressure drop of fluid to pressure drop of mixture flowing at the same velocity) vs. Froude number are also presented.

II. RESULTS OF PREVIOUS WORK

Earlier data on the horizontal flow of a slurry as reported by Murphy, Young, and Burian\(^2\) indicated that the following conclusions could be

---


\(^2\) Ibid.
stated relative to the general flow characteristics of a slurry.

(1) There are three characteristic regions of flow: (a) a high-velocity region characterized by an approximately uniform distribution of solids throughout the tube; (b) a transition region characterized by a non-uniform distribution of solids, but with no stationary layer of particles; and (c) a low-velocity region characterized by a stationary layer of particles.

(2) The upper transition velocity, or boundary between the high velocity and the transition velocity regions, is a function of the particle size, and apparently there is a critical size for each material.

(3) For particles smaller than the critical size the upper transition velocity increases both as the concentration of solid and as the particle size increases. The following equation gives approximate values for the upper transition velocities:

\[ \frac{\rho_f}{\rho_s} \left( \frac{v_{ut}^2}{Dg} \right) = 285 \left[ \frac{d}{D} \frac{e_s}{s} \right]^{0.6} \]

(4) For particles larger than the critical size the upper transition velocity increases as the concentration of solid increases. The following equation gives approximate values for the upper transition velocity:

\[ \frac{\rho_f}{\rho_s} \left( \frac{v_{ut}^2}{Dg} \right) = 75 (e_s)^{1.35} \]

(5) The variation in the lower transition velocity is not sufficiently defined to indicate the variation with concentration and particle size.

In addition, the following relationships were developed for the high-
velocity region of flow.

For particles whose size is less than the critical size, the pressure drop can be expressed as

$$\frac{\Delta P_m}{\Delta P_w} = 0.96 \left( \frac{D}{d} \right)^{0.076} \left( \epsilon_s \right)^{0.113},$$

where $\Delta P_m$ is the pressure drop of the mixture and $\Delta P_w$ is the pressure drop of the pure fluid flowing at the same mean velocity.

For particles whose size is greater than the critical size, the pressure drop can be expressed as

$$\Delta P_m = 1.07 \Delta P_w.$$

In these conclusions it was noted that the critical size depended upon the specific weight of the material, and the value of the critical size was not precisely determined.

### III. MATERIALS AND EQUIPMENT

#### A. Materials

Glass beads and ion-exchange resin particles were used for the solid phases of the slurries, and tap water was used for the liquid phase in the tests. Both types of solid materials were spherical in shape. The glass particles are "Superbrite" glass beads ordinarily used for pavement marking and were obtained from the Minnesota Mining and Manufacturing Company. The resin particles used in the tests were obtained by dry screening with U. S. Standard screens and taking the fraction between
100 and 200 mesh. Size and specific weight determinations were made using the methods described in a previous report.  

Table I lists the properties of the materials tested.

<table>
<thead>
<tr>
<th>Material</th>
<th>Av. Particle Diameter (in.)</th>
<th>Specific Weight (pcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>0.0026</td>
<td>174.2</td>
</tr>
<tr>
<td>Glass</td>
<td>0.0028</td>
<td>154.4</td>
</tr>
<tr>
<td>Glass</td>
<td>0.0013</td>
<td>147.0</td>
</tr>
<tr>
<td>Resin</td>
<td>0.0044</td>
<td>84.1</td>
</tr>
</tbody>
</table>

Figure 1 shows the relationship between concentration by weight and specific weight of the mixture for the materials used in the investigation.

**B. Equipment**

The basic equipment used in the tests included three test sections, a pump and motor unit, a slurry supply tank, a measuring tank and graduated cylinder, platform scales, three differential manometers, and a series of copper and steel nozzles.

The major pieces of equipment used were essentially the same as

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Ibid.
those used to collect the data presented in a previous report. Because the particles were small, the slurry could be pumped directly through a centrifugal pump, and it was not necessary to use the solids feed tank. A series of copper and steel nozzles was used to vary the flow since it could not be adjusted satisfactorily with gate or globe valves.

An injection nozzle was installed at the bottom of the measuring tank so that the pump could be used to force the slurry back into the supply tank and thus eliminate manual handling of the material.

A 1/30 hp Industrial Mixer with a 15-in. shaft and 3-in. propeller was used to maintain a uniform suspension in the supply tank. A copper cooling coil was used to keep the slurry temperature constant.

A bromoform manometer was added to the system to improve the accuracy of pressure-drop measurement in the region in which the pressure differential was too great for the range of the carbon tetrachloride manometer but was too small to provide an appreciable difference on the mercury manometer. A calibrated sight glass was installed in the side of the weighing tank to permit volume measurement to be obtained more easily than by using the piezometer tube.

A two-liter graduated cylinder was used to collect the mixture for low rates of flow.

The glass tube used for upward flow tests was 0.314-in. inside diameter, and the tube used for downward flow was 0.322-in. inside diameter, and the tube used for downward flow was 0.322-in. inside diameter. 

\[ \text{Ibid.} \]
diameter. Both tubes had a test section 36-in. long, with a 32-in. entrance section. The horizontal test section was a glass tube with an inside diameter of 0.315-in. It was 46-in. long, with a 32-in. entrance section.

The slurry was directed out of a horizontal pipe into the upward flow section, through a tygon connecting tube into the downward flow test section, and then through an inclined tube into the weighing tank as shown in Fig. 2.

C. Calibration

The three test-sections were calibrated with water. The turbulent region was found to follow the Blasius equation for smooth pipes, and the laminar region was found to follow the relationship \( f = 64/R \). The transition region occurred within a Reynolds number range of 1500 to 4000. The results of the calibration are shown in Fig. 3.

D. Test Procedure

The test procedure used is summarized by the following outline.

1. The Industrial Mixer was turned on to suspend the particles in the fluid in the supply tank, and the cooling water was turned on.

2. The pump was started, and the slurry was allowed to circulate through the system. The scale was balanced, and the air was bled from the manometer leads. The concentration was adjusted if necessary.

3. When the system had reached an equilibrium condition, the test was started by switching the flow from the supply tank into the measuring
tank (or graduated cylinder). The stop watch was started simultaneously with this action.

4. The following data were taken during the test run: manometer readings, temperature of the mixture, and visual observation of the flow, if significant.

5. If the measuring tank was used, the flow was switched from the measuring tank into the supply tank, and the watch was stopped simultaneously as the beam on the scales passed its balance point. If the graduated cylinder was used, the action took place as the two-liter mark was reached. The weight and volume of the mixture and the time were recorded, the specific weight of the mixture was calculated, and the concentration was found from a plot of specific weight vs. concentration (see Fig. 1).

6. After the data had been recorded, the measuring tank was emptied by pulling the plug in the bottom of the tank and allowing the ejector nozzle to force the mixture back into the supply tank.

7. The pump was then stopped and a different nozzle inserted into the system for a test run at a different velocity.

IV. ANALYSIS

A. Types of Flow

Observation of the horizontal flow of the materials tested indicated that the types of flow are the same as those described in a previous report. 5

5 Ibid.
The three regions are characterized by the particular solids-distribution across the vertical diameter. The high-velocity region has a uniform solids-distribution, the transition region has a non-uniform distribution but no stationary layer of solids, and the low-velocity region has a stationary layer of particles in the bottom of the pipe.

Three distinct regions of flow may also be distinguished in vertical upward flow. The high-velocity region is again characterized by a uniform distribution of solids, but as the velocity is decreased, the flow enters a velocity region in which the particles concentrate in a "core" in the center of the tube leaving a boundary layer of clear fluid between the center core and the inner wall of the tube. As the velocity is decreased further, the solids again appear to be approximately uniform in distribution throughout the tube.

In downward flow the tendency for coring is reversed. That is, in a certain velocity range the solids move toward the outside of the tube, leaving a fluid core. However, it is more difficult to make observations under this condition.

The types of coring described in the foregoing paragraph occur when the density of the solid is greater than the density of the fluid. When the density of the solid is less than the density of the fluid, the coring is reversed. That is, the solids concentrate in a central core with downward flow and in a peripheral annulus when the flow is upward.
**B. Analysis of the Friction Loss**

The initial steps used in this analysis of the problem are identical to those used in the first study discussed in the previous report. For an initial experimental study it is desirable to reduce to a minimum the number of variables that must be investigated. This reduction of the number of variables may be done with dimensional analysis.

The phenomenon is assumed to involve the following variables:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimensions</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta P$</td>
<td>$M L^{-1}T^{-2}$</td>
<td>Pressure drop</td>
</tr>
<tr>
<td>$L$</td>
<td>$L$</td>
<td>Length of tube</td>
</tr>
<tr>
<td>$D$</td>
<td>$L$</td>
<td>Inside diameter of tube</td>
</tr>
<tr>
<td>$d$</td>
<td>$L$</td>
<td>Diameter of particles</td>
</tr>
<tr>
<td>$r$</td>
<td>-</td>
<td>Roughness of tube</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>$M L^{-3}$</td>
<td>Density of fluid</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>$M L^{-3}$</td>
<td>Density of solid</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$M L^{-1}T^{-1}$</td>
<td>Viscosity of fluid</td>
</tr>
<tr>
<td>$\epsilon_s$</td>
<td>-</td>
<td>Concentration of solids</td>
</tr>
<tr>
<td>$v_m$</td>
<td>$L T^{-1}$</td>
<td>Velocity of mixture</td>
</tr>
<tr>
<td>$g$</td>
<td>$L T^{-2}$</td>
<td>Acceleration of gravity</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-</td>
<td>Distribution factor</td>
</tr>
</tbody>
</table>

These twelve variables may be combined into nine independent, dimensionless groups to form the characteristic equation for the phenomenon.
One form of the equation is

\[
\frac{\Delta P}{\rho_f \nu_f^2} = \phi \left[ \frac{L}{D}, r, \frac{\rho_f \nu_m D}{\mu}, \frac{\rho_s}{\rho_f}, c_s, \frac{d}{D}, \frac{\nu_f^2}{Dg}, \alpha \right]
\]  \hspace{1cm} (1)

If the fluid carries no solid particles, the last five terms in Eq. (1) are not involved, and the equation reduces to

\[
\frac{\Delta P}{\rho_f \nu_f^2} = \phi_1 \left[ \frac{L}{D}, r, \frac{\rho_f \nu_f D}{\mu} \right]
\]  \hspace{1cm} (2)

It is known that the variable, \(L/D\), is separable when it has a value greater than approximately 20, so that

\[
\frac{\Delta P}{\rho_f \nu_f^2} = \frac{L}{D} \phi_2 \left[ r, \frac{\rho_f \nu_f D}{\mu} \right]
\]  \hspace{1cm} (3)

The function \(\phi_2\) is usually replaced by a coefficient, \(f/2\), making it possible to rewrite Eq. (3) as

\[
\frac{\Delta P}{\rho_f \nu_f^2} = f \frac{L}{D}, \frac{\rho_f \nu_f^2}{2}
\]  \hspace{1cm} (4)

or

\[
\Delta P = f \frac{L}{D} \frac{\rho_f \nu_f^2}{2}
\]  \hspace{1cm} (5)

Equation (5) may also be written in terms of the head loss, \(H_f\).

Thus,

\[
H_f = f \frac{L}{D} \frac{\nu_f^2}{2g}
\]  \hspace{1cm} (6)

which is the familiar Darcy Equation for head loss in a pipe. Charts have been developed for evaluating \(f\) for known values of the Reynolds number, \(\frac{\rho_f \nu_f D}{\mu}\), and the pipe roughness, \(r\).
In extending the results to the flow of slurries it was assumed in this investigation that the quantity L/D in Eq. (1) was still separable, so that

\[
\frac{\Delta P}{\rho_f \eta_m^2} = \frac{L}{D} \phi_3 \left[ r, \frac{\rho_f \eta_m^2}{\mu}, \frac{\rho_s}{\rho_f}, e_s, \frac{d}{D}, \frac{\eta_m^2}{Dg}, \alpha \right]
\] . (7)

It appeared reasonable to assume that \( \phi_3 \), in Eq. (7), could be resolved into two component terms—one being the friction factor of the fluid alone (f) and the other being the ratio of the pressure loss for the pure fluid to the pressure loss of the mixture if both are flowing at the same mean velocity (Z). If this assumption is made, Eq. (7) becomes

\[
\frac{\Delta P}{\rho_f \eta_m^2} = \frac{L}{D} \frac{f}{Z} \frac{1}{Z}
\] , (8)

or

\[
H_f = \frac{\eta_m^2}{2g} \frac{L}{D} \frac{f}{Z}
\] , (9)

where

\[
Z = \frac{\Delta P_f}{\Delta P_m}
\] , (10)

and where \( H_f \) is the head loss of the mixture in an equivalent column of pure fluid.

From a comparison of Eqs. (7) and (8), it appears reasonable to assume that Z is a function of those variables in \( \phi_3 \), that are not included in f. Then

\[
Z = \phi_4 \left[ \frac{\rho_s}{\rho_f}, e_s, \frac{d}{D}, \frac{\eta_m^2}{Dg}, \alpha \right]
\] . (11)
Experimental tests are now being conducted to determine the function, $\phi_4$. The scope of the tests conducted is indicated in Table II.

The calculation of the Z-factor is made in the following way. The pressure drop of the mixture is measured experimentally, and the mean velocity of the mixture is found from the measured discharge of the mixture. The pressure drop of the pure fluid is calculated using the mean velocity of the mixture and a value of the friction factor ($f$) found from the calibration curve. The Reynold's number is calculated using the mean mixture velocity and the properties of the pure fluid at the measured temperature. The Z-factor is the ratio of the pressure drop of the pure fluid to the pressure drop of the mixture flowing at the same mean velocity.
Table II.
Scope of the Test Program

<table>
<thead>
<tr>
<th>Direction</th>
<th>Material</th>
<th>Particle Diameter (in.)</th>
<th>Tube Diameter (up/down) (in.)</th>
<th>Tube Length (in.)</th>
<th>Concentration Range (percent by weight)</th>
<th>Velocity Range (fps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>Glass</td>
<td>0.0026</td>
<td>0.314</td>
<td>46</td>
<td>5 - 50</td>
<td>0.5 - 16.5</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>0.0013</td>
<td>0.315</td>
<td>46</td>
<td>5 - 30</td>
<td>0.6 - 23.8</td>
</tr>
<tr>
<td></td>
<td>Resin</td>
<td>0.0044</td>
<td>0.315</td>
<td>46</td>
<td>8 - 35</td>
<td>0.4 - 19.6</td>
</tr>
<tr>
<td>Vertical</td>
<td>Glass</td>
<td>0.0028</td>
<td>0.314/0.322</td>
<td>36</td>
<td>5 - 50</td>
<td>0.4 - 15.0</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>0.0013</td>
<td>0.314/0.322</td>
<td>36</td>
<td>5 - 40</td>
<td>0.6 - 16.0</td>
</tr>
<tr>
<td></td>
<td>Resin</td>
<td>0.0044</td>
<td>0.314/0.322</td>
<td>36</td>
<td>4 - 46</td>
<td>0.6 - 13.5</td>
</tr>
</tbody>
</table>
V. DISCUSSION

The experimental data obtained in the tests are tabulated in Appendix B. The variation of the pressure drop with Froude number for different concentrations of solid material is shown in two types of figures. The first is a plot of the friction loss of the slurry vs. the Froude number, based on the mean velocity of the mixture and the inside diameter of the test section. The second type is a plot of the ratio of the pressure drop of the pure fluid to the pressure drop of the mixture flowing at the same mean velocity (Z-factor) vs. the Froude number.

The actual reduced data for a representative concentration are shown for each type of material and for each direction of flow. The results for all concentrations are shown in the form of average curves for each material and each direction of flow. These figures are given in Appendix A and will be discussed in this section.

Figures 7, 8, and 9 are curves of head loss in feet of mixture vs. Froude number, for the three materials tested in horizontal flow and for the concentration ranges investigated. A study of the data showed that the upper-transition velocity (the velocity at which the head loss curve, on logarithmic paper, departs from the straight line portion) is dependent upon the particle size and solid concentration. For the materials and size ranges tested, there was no indication of critical size, and as a result the following expression was developed for the
upper transition velocity:

\[ \frac{v_{UT}}{Dg} = 3.23 + 195 \left( \frac{d}{D} \right)^2 - 31,400 \left( \frac{d}{D} \right)^2 - \left[ 18.5 - 5060 \left( \frac{d}{D} \right) + 143,000 \left( \frac{d}{D} \right)^2 \right] e_s. \]

Plots of Froude number (based on the lower transition velocity) vs. \( e_s \) for the materials tested indicate that the expression for the lower-transition velocity would have the same general form as that for the upper-transition velocity except that the ratio \( \rho_s/\rho_l \) might appear in the function.

At velocities greater than the upper-transition velocity, the head loss vs. Froude number curves generally all lie parallel to, and above, the same curve for water. The distance between the curve for the slurry and that for water increases with an increase in concentration, indicating that for a given Froude number an increase in concentration will cause an increase in head loss.

The curve for \( e_s = 35 \) percent in Fig. 9 illustrates a condition which does not agree with the pattern just discussed. For values of Froude number greater than approximately 30, a straight line portion exists but has a steeper slope than the same curve for water. For Froude numbers between nine and thirty, the curve dips below the curve for water, and for values of Froude number less than ten, the curve is approximately straight with a slope slightly less than that for the curve for water in laminar flow.

If laminar and turbulent regions of flow are defined on the basis of the characteristic slope of the respective head loss curves, then the
$e_s = 35\text{ percent curve for the 0.0044-in. resin in horizontal flow can be considered to exhibit evidences of laminar and turbulent flow. For Froude numbers up to approximately ten this curve indicates laminar flow of the slurry, and for Froude numbers greater than thirty turbulent flow can be considered to exist. The region between Froude numbers of ten and thirty represents the transition from one type of flow to the other.}

Figures 10 through 18 include the curves of head loss vs. Froude number for upward and downward vertical flow of the materials for the concentrations investigated. In all of these curves, it is to be noted that the same general behavior results as that described for the $e_s = 35\text{ percent curve for the 0.0044-in. resin in horizontal flow. For all three materials in the turbulent region (where the head loss vs. Froude number curve is parallel to the same curve for water in turbulent flow) the head loss increases slightly with an increase in concentration. At high concentrations (e.g., $e_s = 35\text{ percent or greater}$) the slope of the slurry head loss curve in the turbulent region has a tendency to become slightly greater than that for the same curve for water in turbulent flow.}

In the laminar region, the head loss curves for the 0.0044-in. resin and the 0.0028-in. glass in downward flow lie above the same curves for upward flow, and the slopes of these curves are generally slightly less steep than the upward flow curves.
The data for the laminar flow of the 0.0013-in. glass indicate that the head loss curve for upward flow lies above that for downward flow, which is the reverse of the condition noted in the 0.0044-in. resin and the 0.0028-in. glass.

It was also noted that the velocity at which transition from laminar to turbulent flow takes place is dependent upon the concentration. The transition velocity increases with increasing concentration. The facts that the laminar region for the slurry extends to much higher Froude numbers than for the pure water and that the transition velocity increases with concentration, suggest that the presence of the particles in the fluid exerts a calming or dampening effect on the turbulence, tending to maintain laminar flow at higher than ordinary velocities.

Representative plots of actual reduced data for the upward and downward flow of the materials investigated are shown in Figs. 16, 17 and 18.

Figures 22 through 27 are plots of calculated Z-factors vs. Froude number for representative concentrations for the materials tested and the different directions of flow. Figures 28 through 36 are average curves for each material at the various concentrations tested.

It was noted that the Z-factors were constant for a certain range of Froude numbers, depending upon the material used and the direction of flow. This was considered to be the region of turbulent flow, or the region in which the particles were uniformly distributed throughout the tube. As the Froude number decreases, the slurry flow enters the
transition region, or the region in which the particles are not uniformly distributed throughout the tube. This region is the curved portion of the Z-factor curves. A further decrease in Froude number results in a corresponding decrease in the Z-factor. This region is the straight-line portion of the Z-factor curves at low Froude numbers. It appears that in this range the slurry has the characteristics of laminar flow. This straight-line portion is also noticed on the head loss vs. Froude number curves, particularly those representing vertical flow of the 0.0044-in. resin particle slurries which were discussed earlier.

It was also noted that the Z-factors in the transition region (curved portion of the curves) sometimes have a value greater than one, which means that the pressure loss due to friction of the slurry is less than that of water flowing at the same velocity. Again, this is particularly noticeable in the data for the resin slurries in vertical flow.

In the turbulent region the Z-factors decrease with increasing concentration. The values of the Z-factor for turbulent flow were found for each direction of flow and were plotted against the concentration. The resulting curves are shown in Figs. 4, 5 and 6.

The following relationships were found from these curves.

<table>
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<th>Direction</th>
<th>0.0013-in. glass</th>
<th>0.0028-in. glass</th>
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<td>( Z = 0.972 - 0.0078 e_s )</td>
<td>( Z = 1.08 e_s^{-0.125} )</td>
</tr>
<tr>
<td>Upward</td>
<td>( Z = 0.850 - 0.0063 e_s )</td>
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<td>( Z = 0.927 - 0.00715 e_s )</td>
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where \( e_s \) = concentration in percent by weight.
The following conclusions are drawn from the study of the head loss curves and observations of the flow.

Horizontal Flow

(1) There are three distinct regions of flow: (a) a high velocity region characterized by an approximately uniform distribution of solids throughout the tube; (b) a transition region characterized by a non-uniform distribution of solids but with no stationary layer of particles; and (c) a low velocity region characterized by a stationary layer of particles in the bottom of the tube.

(2) The upper transition velocity, or velocity at which the head loss curve departs from the straight-line portion on a logarithmic plot, is a function of concentration and particle size and can be expressed by the relationship

\[
\frac{v^2 UT}{gD} = 3.23 + 195 \left( \frac{d}{D} \right) - 31,400 \left( \frac{d}{D} \right)^2 - \left[ 18.5 - 5060 \left( \frac{d}{D} \right) + 143,000 \left( \frac{d}{D} \right)^2 \right] \epsilon_s,
\]

which holds for the three materials tested.

(3) In the turbulent region for a given Froude number, the head loss increases slightly with increasing concentration.

Vertical Flow

(1) The three materials tested exhibit regions of laminar and turbulent flow which are characterized by the slope of the head loss vs. Froude number curve.

(2) The velocity at which transition from laminar to turbulent flow begins to occur increases with increasing concentration for a given material.
(3) The head loss curves for laminar flow for the 0.0044-in. and the 0.0028-in. glass in a downward direction, lie above the same curves for upward flow, indicating a higher head loss in this region for downward flow than for upward flow.

The following general statements may be made from a study of the Z-factor curves in the turbulent region.

In horizontal flow, the greatest pressure drop occurs with the 0.0028-in. glass, while the pressure drop is about the same for the other two materials.

In upward flow, the greatest loss occurs with the 0.0013-in. glass, while the least pressure drop occurs with the resin particles.

In downward flow, the tendency is the same as that for horizontal flow.

In regard to the specific materials in turbulent flow for a particular concentration and velocity, the following statements may be made.

For the 0.0013-in. glass, the pressure drop for horizontal flow is less than that for vertical flow in either direction. The pressure drop for downward flow is less than that for upward flow.

For the 0.0028-in. glass, the pressure drop is about the same in all directions.

For the 0.0044-in. resin, the greatest pressure drop occurs in downward flow, while the least pressure drop occurs in horizontal flow.
VI. APPENDIX

A. Graphic Data

(Figures 1-36)
Fig. 1—Relationship between concentration and specific weight for materials used in the investigation.
Fig. 2—Schematic diagram of flow equipment.
Fig. 3—Calibration curve for experimental equipment.
Fig. 4—Relationship between Z-factor in turbulent flow and concentration for 0.0028-in. dia. glass particles.
Fig. 5—Relationship between Z-factor in turbulent flow and concentration for 0.0013-in. dia. glass particles.

0.0013-IN. DIA. GLASS BEADS

- X HORIZONTAL FLOW
- O UPWARD FLOW
- △ DOWNWARD FLOW

\[
\frac{\rho_s}{\rho_f} = 2.356
\]
\[
\frac{d}{D} = 0.00413 \text{ (UPWARD)}
\]
Fig. 6—Relationship between Z-factor in turbulent flow and concentration for 0.0044-in. dia. resin particles.
Fig. 7—Average head loss curves for 0.0026-in. diam. glass in horizontal flow.
Fig. 8—Average head loss for 0.0013-in. dia. glass in horizontal flow.
Fig. 9—Average head loss curves for 0.0044-in. dia. resin in horizontal flow.
Fig. 10—Plot of actual head loss data for horizontal flow of 0.0026-in. dia. glass (30 percent).
Fig. 11—Plot of actual head loss data for horizontal flow of 0.0013-in. dia. glass (20 percent).
Fig. 12—Plot of actual head loss data for horizontal flow of 0.0044-in. dia. resin (35 percent).
Fig. 13—Average head loss curves for 0.0028-in. dia. glass in upward flow.
Fig. 14—Average head loss curves for 0.0013-in. dia. glass in upward flow.
Fig. 15—Average head loss curves for 0.004-in. dia. resin in upward flow.
Fig. 16—Average head loss curves for 0.0028-in. dia. glass in downward flow.
Fig. 17—Average head loss curves for 0.0013-in. dia. glass in downward flow.
Fig. 18—Average head loss curves for 0.0044-in. dia. resin in downward flow.
Fig. 19—Plot of actual head loss data for vertical flow of 0.0028-in. dia. glass (30 percent).
Fig. 20—Plot of actual head loss data for vertical flow of 0.0013-in. diam. glass (5 percent).
Fig. 21—Plot of actual head loss data for vertical flow of 0.0044-in. dia. resin (35 percent).
Fig. 22—Plot of Z-factors for horizontal flow of 0.0026-in. dia. glass (30 percent).
Fig. 23—Plot of Z-factors for horizontal flow of 0.0013-in. dia. glass (20 percent).
Fig. 24—Plot of $Z$-factors for horizontal flow of 0.0044-in dia. resin (35 percent).
Fig. 25—Plot of Z-factors for vertical flow of 0.0028-in. dia. glass (25 percent).
Fig 26—Plot of Z-factors for vertical flow of 0.0013-in dia glass (30 percent).
Fig. 27—Plot of Z-factors for vertical flow of 0.0044-in. dia. resin (23.5 percent).
Fig. 28—Average Z-factor curves for horizontal flow of 0.0026-in dia. glass (All concentrations).
**Fig. 29**—Average Z-factor curves for horizontal flow of 0.0013-in. dia. glass (All concentrations).
Fig. 30—Average Z-factor curves for horizontal flow of 0.0044-in. dia. resin (All concentrations).
Fig. 31—Average Z-factor curves for upward flow of 0.0028-in. dia. glass (All concentrations).
Fig. 32—Average Z-factor curves for upward flow of 0.0013-in. dia. glass (All concentrations).
Fig 33—Average Z-factor curves for upward flow of 0.0044-in.
inch resin (All concentrations).
Fig. 34—Average Z-factor curves for downward flow of 0.0028-in. dia. glass (All concentrations).
Fig. 35—Average Z-factor curves for downward flow of 0.0013-in. dia. glass (All concentrations).
Fig. 36—Average Z-factor curves for downward flow of 0.0044-in. α₃ resin (All concentrations).
B. Tabulated Data

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Table II. Scope of the Test Program....................................... 18

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Table IV. 0.0013-in. dia. glass-horizontal flow......................... 70

Table V. 0.0044-in. dia. resin-horizontal flow.......................... 72

Table VI. 0.0028-in. dia. glass-vertical flow............................ 75

Table VII. 0.0013-in. dia. glass-vertical flow........................... 86

Table VIII. 0.0044-in. dia. resin-vertical flow.......................... 90
### Table III.

0.0026-in. Dia. glass; horizontal flow

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0.0028-in. Dia. glass; vertical flow

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0.0013-in. Dia. glass; vertical flow

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